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Taiwan's GHG mitigation potentials and costs: An evaluation with the MARKAL model

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A R T I C L E I N F O

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A B S T R A C T

The post-Kyoto negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) have produced significant results such as the Bali Roadmap, Copenhagen Accord and Cancun Agreement, and clarified parties' plans for long-term emissions mitigation. This paper presents the results on the simulations of different technology development scenarios under the same emission reduction goal, utilizing the MARKAL model to evaluate emissions reduction on Taiwan's electricity, industry, buildings, and transportation sectors. The empirical results show that Taiwan can potentially reduce 56%–60% of greenhouse gas emissions relative to the BAU scenario in 2025, and 15% relative to the 2005 levels. These projected results are higher than the Kyoto targets of Annex I countries and also higher than those projected in the (IEA, 2011 [17]) and (EIA, 2011 [5]) scenarios. The accumulated incremental cost will be an increase by 1.2%–1.96% of Taiwan's GDP.

As Taiwan heavily relies on imported energy from foreign sources and has very limited natural endowments of renewable energy, it is very difficult for Taiwan to reach this reduction goal alone through adopting emission reduction technology, or applying economic incentive mechanism. Allowing Taiwan to participate in the international flexible mechanisms will be a necessary measure for Taiwan to achieve its emission reduction goal; in addition, such participation will also benefit the international community's GHG reduction efforts tremendously.

Contents

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1. Introduction

Since 1992, the world has been through nearly20 years of climate negotiations, but the global greenhouse gas (GHG) emissions are still locked in its highest growth rate ever recorded. This result is inconsistent with the claims that developed countries are determined to reduce their GHG emissions in order to mitigate the climate change effects. The UNFCCC Copenhagen Conference (COP 15) held in Dec. 2009 adopted the Copenhagen Accord which aims to restrict the global temperature rise within two degree Celsius, and asks Annex I countries to submit quantitative reduction commitments for 2020 [41]. and non-Annex I countries to submit information regarding their Nationally Appropriate Mitigation Actions (NAMAs). Moreover, low-emissions development strategies and plans have become essential inputs for many parties (including United Kingdom, European Union, and Japan, etc.) in their planning for the mid to long-term (2020–2050) climate plans [1,4,6,7,9-14,19,20,22–27,32,35–38,40].

Though Taiwan is not a party to the UNFCCC, under the consensus and pressure of global environmental integrity, Taiwan certainly can be asked for emissions reduction by UNFCCC parties. Thus, Taiwan's government has proactively announced the CO_2 reduction goal and schedule before the consensus of the international climate negotiations that Taiwan will return to its 2005 emission levels by 2020 and 2000 emission levels by 2025. In addition, Taiwan also announced that it will submit NAMAs to the international community and pledged to fulfill its international responsibility regarding the global warming issue.

The United Kingdom,[1] Japan,[2] and IPCC's[3] greenhouse gas reduction strategies all stressed changes in economic and social activities, reduction of energy demand, and improvement of energy intensity (such as switching fuels or adopting advanced innovative technology). Every country has its unique energy and resource endowment, economic development and social conditions, and each country shall be able to select minimum cost solutions based on their national circumstances, to establish related emission reduction measures. This study has employed the social and economic situations and assumptions which were concluded in Taiwan's NAMAs Negotiation Meeting, in order to estimate the energy service demand in Taiwan's industry, buildings and transportation sectors. It then adopted the GDP growth rates of the Reference Scenario, and utilized the Taiwan MARKAL model to analyze the effects of energy structure and incremental costs of these four sectors in adopting low GDP growth rate and CO_2 emission targets during the short to mid-term period. Besides this Introduction Section, this paper also includes Section 2 on methodology and approach, Section 3 on simulation results, Section 4 on discussions, and the final section dealing with the conclusion.

2. International GHG reduction trend

2.1. Energy consumption trend

Energy is the power source of all human activities, but it is also the major source of anthropogenic CO_2 emissions. Based on the two crises, fossil energy reserves, and Environmental Protection, major economies strive hard to reduce energy consumption, protect energy security, and improve energy productivities.

2.1.1. Primary energy supply

Table 1 below shows the primary energy supply growth rates in major developed countries (e.g., EU, Germany, UK, USA, and Japan) since 1971, with a decreasing trend. During 2001–2009, negative grow rates can even be observed for these economies. In Asia, energy supply growth rates of Korea and Taiwan are lower for the same period when compared with previous decades, but China's high growth rate continued because of its continuing rapid GDP growth.

2.1.2. Energy security

The two oil crises during the 1970s prompted countries to pursue energy security and independence, though with different results, as shown in Table 2 below. During the 1981–2009 period, OECD-Europe, the United Kingdom and the United States all began with net energy import dependence of less than 0.5, but are all showing increasing trend in energy imports. Germany also gradually increased its energy imports during this period, and saw its energy import dependence increased to 0.62 during 2001–2009. Asian economies, such as Japan, Korea, and Taiwan, are

Table 1
Primary energy supply growth rates of major economies (1971–2009).
Source: OECD database [33].

	Unit: %			
	1971–1980	1981–1990	1991–2000	2001–2009
World	2.70	2.06	1.33	2.26
OECD Europe	1.86	1.12	0.63	0.20
Germany	1.59	0.18	−0.23	−0.57
United Kingdom	−0.50	0.68	0.46	−0.99
United States	1.29	0.88	1.65	−0.07
Japan	2.56	2.69	1.57	−0.28
Korea	9.28	8.69	6.53	2.73
China (including Hong Kong)	4.36	3.93	3.29	7.17
Taiwan	10.82	6.40	5.11	2.06

[1] UKERC [39].
[2] NIES [30].
[3] IPCC [21].

Table 2
Energy import dependences of major economies (1971–2009).
Source: OECD database [33].

	1971–1980	1981–1990	1991–2000	2001–2009
World	−0.01	0.00	0.00	0.00
OECD Europe	0.53	0.38	0.37	0.44
Germany	0.51	0.46	0.59	0.62
United Kingdom	0.37	−0.10	−0.11	0.12
United States	0.18	0.14	0.22	0.29
Japan	0.96	0.86	0.83	0.83
Korea	0.68	0.73	0.90	0.87
China (including Hong Kong)	−0.01	−0.03	0.01	0.08
Taiwan	0.80	0.79	0.90	0.92

Table 3
Energy intensities of major economies (1970–2009).
Source: OECD database [33].

	Unit: toe per US$ (2005 USD PPP)			
	1971–1980	1981–1990	1991–2000	2001–2009
World	0.28	0.25	0.25	0.20
Annex I Parties				0.17
Annex I Kyoto Parties				0.16
Europe	0.19	0.16	0.16	0.12
Germany	0.23	0.20	0.20	0.13
United Kingdom	0.23	0.18	0.18	0.11
United States	0.34	0.26	0.26	0.18
Japan	0.19	0.14	0.14	0.13
Korea	0.20	0.19	0.19	0.19
China	1.16	0.75	0.75	0.29
Taiwan	0.20	0.18	0.18	0.17

Table 4
CO_2 emissions growth rates of major economies (1970–2010).
Source: IEA [18].

	1971–1980	1981–1990	1991–2000	2001–2010
World	0.025	0.016	0.010	0.027
Annex I Parties			−0.001	−0.002
Annex I Kyoto Parties			−0.012	−0.002
Europe	0.009	−0.001	0.000	−0.007
Germany	0.008	−0.007	−0.011	−0.012
United Kingdom	−0.010	−0.000	−0.006	−0.011
United States	0.011	0.005	0.016	−0.004
Japan	0.019	0.018	0.012	−0.002
Korea	0.087	0.066	0.059	0.026
China	0.058	0.048	0.027	0.088
Taiwan	0.089	0.055	0.058	0.018

even more dependent on imported energy, each with current energy import dependence of higher than 0.8. Japan has been gradually reducing its import dependence since the 1970s, while Korea is also working on decreasing import dependency during the past decade. Before the 1990s, China was originally a net exporter of energy, but due to its rapid industrial growth, its dependence of energy imports has increased to the current 0.08.

2.1.3. *Energy intensities*

The energy intensities of major economies continue to decline during 1970–2009 (see Table 3), mainly due to the greater positive GDP growth rates than the negative energy supply growth rates. China is no exception to this trend, because of its high rates of GDP growth.

2.2. *CO_2 emissions*

During 1971–2010, the world's major economies not only reduced energy consumption but also CO_2 emissions, with most economies' CO_2 emissions growth rates gradually decline except China (Table 4). In particular, developed countries are showing a negative growth trend currently.

In order to grasp the main sources of carbon dioxide emissions, and take effective measures to reduce CO_2 emission. We use the Kaya's equation to analysis CO_2 emission factors contribution. The Kaya equation[4] Eq. (1) is as follows:

$$CO_2 = \frac{CO_2}{\text{Energy consumption}} \times \frac{\text{Energy consumption}}{\text{GDP}} \times \frac{\text{GDP}}{\text{Population}} \times \text{population}$$

$$\Delta CO_2 = \frac{\Delta CO_2}{\Delta \text{Energy consumption}} \times \frac{\Delta \text{Energy consumption}}{\Delta \text{GDP}} \times \frac{\Delta \text{GDP}}{\Delta \text{Population}} \times \Delta \text{population} \quad (1)$$

Terms of the Kaya factorization for CO_2 emission factors contribution are shown in Fig. 1 below. It can seen from Fig. 1 that the main reason for the increase in global CO_2 emissions during the 2001–2009 period is GDP growth, followed by population growth. Developed countries (including Europe, Germany, UK, USA and Japan) reduced their CO_2 emissions mainly due to decline in energy intensities. By comparison, Fig. 2 shows the major increases in CO_2 emissions for developing countries (including South Korea, China and Taiwan) related to GDP growth. Both South Korea and Taiwan are able to mitigate their recent growth of CO_2 emissions, mainly due to decline in their energy intensities.

2.3. *Carbon reduction targets*

After Cancun COP meeting, many countries have already announced their carbon reduction targets for the mitigation of greenhouse gas concentrations in the atmosphere, covering short-term to long-term periods as shown in Table 5 below. The developed countries'CO_2 targets are between −17% and −34% of BAU emission levels in 2020, while the developing countries' CO_2 targets are between −16% and −30% of BAU emission levels in 2020, similar to those of the developed countries.

2.4. *GHG mitigation scenario*

Prior to the above parties' commitments to emissions reduction targets, the United Kingdom introduced the "Low Carbon Society" initiative, which was subsequently adopted by several UNFCCC Annex I parties such as Japan, Europe Union, and Non-Annex I parties such as Korea. The assumptions and conditions of simulated future Low Carbon Society scenarios for Ref. [17],[5] United Kingdom,[6] USA Ref. [5],[7] Japan-2009,[8] and Korea[9] are listed in Annex Table 1, with the BAU definitions containing "Current Policies" and "Reduction Scenario" in turn to set different technology development speeds. The assumptions of CO_2 target, energy demand growth rate and energy intensity reduction rate of Refs. [17], [5] and Japan-2009 scenarios in 2025 are listed in Table 6.

[4] Developed by Yoichi Kaya, an engineer at Tokyo University.
[5] IEA [17].
[6] UKERC [39].
[7] EIA [5].
[8] NIES [31].
[9] Korea [24].

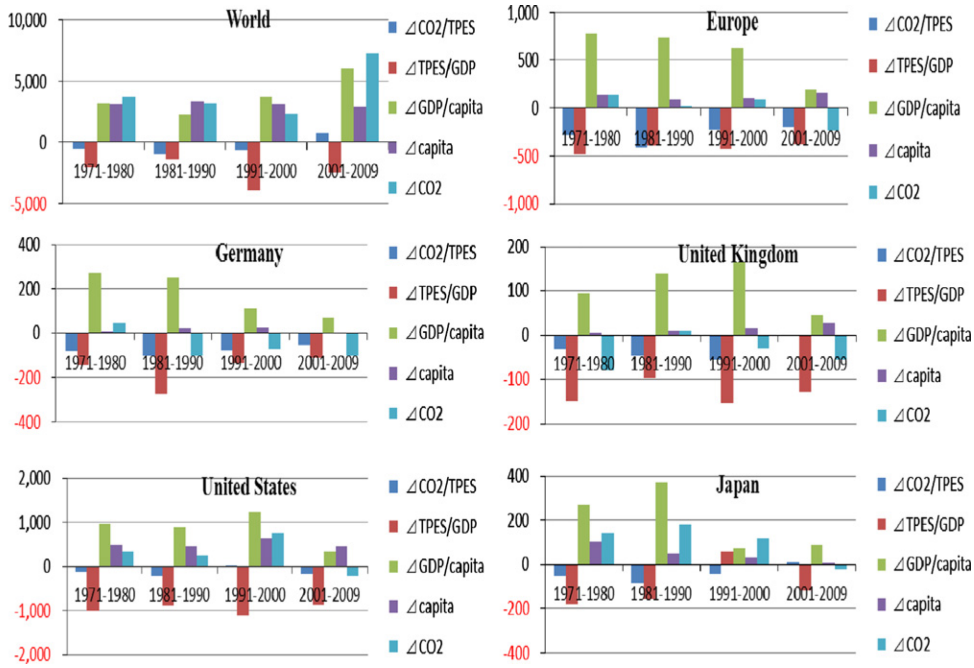

Fig. 1. Kaya factorization CO_2 emission factors contribution by world and developed countries.

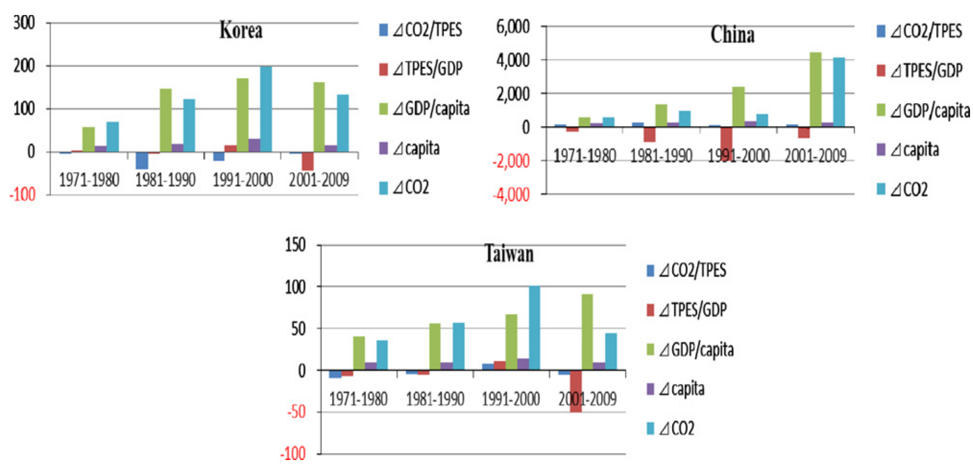

Fig. 2. Kaya factorization CO_2 emission factors contribution by developing countries.

2.4.1. WEO-2011

Under the New Policy Scenario of World Energy Outlook 2011 [17], due to adoption of major energy efficiency enhancement measures (including enhancement of fossil energy service efficiency), the average annual growth rate of global primary energy demand is 1.4% from 2008 to 2020, and will slow down to 0.9% from 2020 to 2035. In Ref. [17], the forecasted average global energy intensity will decrease by 1.2% per year from 2008 to 2035 in the Current Policy Scenario, while the average global energy intensity in the New Policy Scenario will decrease 1.5% per year, and the average global energy intensity in the 450 Scenario will decrease by an even greater 1.9%.

The energy efficiency measures include enhance fossil energy use efficiency (e.g., high efficiency coal-fired boilers and high efficiency coal-fired power generation of non-OECD countries) and reduce energy demand (e.g., high efficiency equipment). High CO_2 prices accelerate the adoption of high-efficiency equipment and development of CCS technology. CO_2 reduction rate due to renewable energy (including biofuels) is from 19% in 2020 to 24% in 2035. High CO_2 prices make renewable energy more competitive. For example, the United States' wind power generation in the 450 Scenario will become market competitive by as early as 10 years when compared with the Current Policy Scenario.CCS technology remains as the main emission reduction strategy after 2030, decreasing emissions 1.7 $GtCO_2$in 2035 (19% of the total CO_2 reduction amount).

2.4.2. AEO-2011

Ref. [5] considered economic growth rate, expanded use of renewable energy technology, energy efficiency enhancement, electricity demand mitigation and use of natural gas. In its No Sunset Case, the total energy consumption is similar to the Reference Case, while in the Extended Policies Case, due to its strict energy efficiency standards the total energy consumption in 2035 is 7% lower than in the reference case.

The reference case assumed fast growing service sector, and the IT industry moving towards development of high value-added

Table 5
Carbon reduction targets announced by UNFCCC parties.
Source: IEA [16].

Country	Base year	Target		Note
		CO_2	Energy saving	
Australia	2000	2020: −5%–15%		Copenhagen Accord
Austria	2006		2016: −9%	EU Directive 2006/32/EC [8], Copenhagen Accord
Brazil		2020: −15MT		Copenhagen Accord
Canada	2005	2020: −17% 2050: −60%		Copenhagen Accord
Czech			2008–2016: −9%	EU Directive 2006/32/EC [8], Copenhagen Accord
Denmark			2006–2013: −7.5 PJ	EU Directive 2006/32/EC [8], Copenhagen Accord
EU	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Finland		2020: −20%	2008–2016: -9% (Minimum energy saving rate)	Copenhagen Accord
France	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Germany	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Greece	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Hungary	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Ireland	1990	2020: -20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Netherlands	1990	−20%	−9% (base year 2006)	
Norway	1990	2020: −30%		Voluntary
Italy	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Portugal	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Spain	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Sweden	1990	2020: −20%	2008–2016: −9% (Minimum energy saving rate)	EU Directive 2006/32/EC [8], Copenhagen Accord
Swiss	1990	2020: −20%		EU Directive 2006/32/EC [8], Copenhagen Accord
UK	1990	2020: −34% 2010: building −3.5 Mt (2000 base year −20%)	2016: −2006 level 34%	EU Directive 2006/32/EC [8], Copenhagen Accord
US	2005	2020: −17%		
New Zealand	1990	2020: −10% to −20%		Voluntary
Mexico		2012: −51 Mt 2020: BAU −30%		
Singapore		2020: BAU −16%	2030: BAU −30%	Copenhagen Accord
Korea	2007	2020: BAU −30%	2012 energy efficiency +11.3% 2020:Existed building energy consumption −30%–40%	Copenhagen Accord
China	2005	2020:CO_2/GDP −40% to −45%		Voluntary Copenhagen Accord
India	2005	2020:CO_2/GDP −20%		Voluntary
Indonesia			2025: Energy intensity −1%/yr	
Vietnam		2011–2015: −5% to −8%	2006–2010: −5%	National Programme on Energy Efficiency and Conservation(2006)
South Africa		2020: BAU −16% 2025: BAU −42%		Copenhagen Accord

industrial structure. It also considered the economic growth rate, expanding use of renewable energy technologies, energy efficiency enhancement, wider natural gas use, and slowing electricity demand, in addition to vehicle emission standards, thus in the reference case the CO_2 emissions grow slowly.

Major emission reduction measures adopted in the no sunset case are renewable energy power generation. In this case, the emission reduction in the transportation sector is small, due to the increase carbon emissions caused by biofuel refining process which offsets the emission reduction from increasing renewable power generation. In the extended policies case, there is more renewable energy power generation, and less fossil fuel demand than the reference case. For both no sunset case and extended policies case, residential sector's hot water, air conditioning, and space heating needs have a greater share in CO_2 reduction, while the service sector in the extended policies case is more important in terms of carbon reduction. The light-duty vehicles (LDVs)'s fuel efficiency standard accounts for half of the carbon reduction, while the other half comes from equipment's energy efficiency improvements and renewable energy power generation.

Table 6
CO_2 targets of international low carbon society scenarios in 2025.

		WEO		AEO			Japan		Korea
		New policies scenario	450 scenario	No sunset	Extended policies	Technology advance	Technology advance (nine new nuclear plants)	Technology advance (substantial CO_2 emission reduction)	(Energy intensity)
CO_2 target	Lower than BAU (%)	9	21	0.7	4.6	13	13	22	
	lower than 2005 (%)	27	−11	1.4	5.3	25	25	32	
Average energy demand growth rate (2010–2025)	(%)	1.5		Similar to BAU	7% lower than BAU		−0.1%	−0.1%	
Energy intensity in 2025	(toe/ US$)	0.13	0.15	0.14	0.14	0.13	0.07	0.07	0.19
Energy per capita in 2025	(tonne/ per capita)	1.96	2.24	7.60	7.56	7.29			

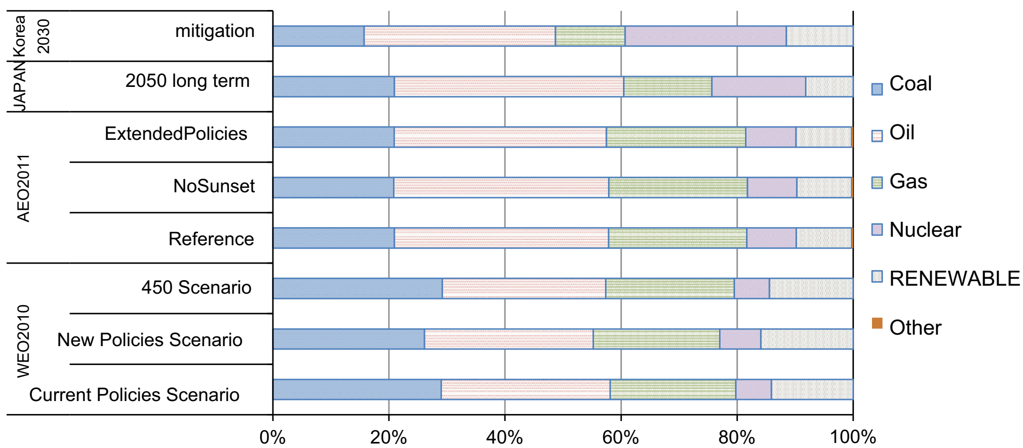

Fig. 3. Primary energy demand structure of the international low carbon society scenario in 2025.
Source: IEA [17], USEIA (2011), NIES [30,31], Korea [24].

2.4.3. Japan-2009

In the Japan-2009 Scenario, the primary energy supply growth slows down due to energy efficiency upgrade, economic and industrial transformation and population decrease. The extent of this reduction will be greatest for the crude oil, and it is expected that the share of oil to total primary energy supply will decrease to 37% in 2030, and the share for coal will also decrease from 21% in 2005 to 18% in 2030. In the BAU Scenario, Japan's energy saving measures reduce CO_2 emissions by 1.6% per year (including 0.4% of annual CO_2 emissions reduction through fuel conversion), while in the Technology Advance Scenario, fuel conversion reduces the annual CO_2 emissions by 0.7%.

2.4.4. Korea-2009

The Government of the Republic of Korea announced the "Green New Deal Policy" promotion program in 2009. This program can be divided into three major areas: green social infrastructure (Social Overhead Capital, SOC), low carbon and high-efficiency industrial technology, and environmental-friendly/green living. Funding for this program is US$36 billion for the 2009–2012 period. Through this program the Korean government hopes to guide green investments, create jobs, stimulate domestic economic growth and create momentum for Korea's future growth.

According to Korea's National Basic Energy Plan, the share of coal in the primary energy supply will gradually decrease from 25.3% in 2007 to 15.7% in 2030, and the share for oil will decrease to 33.0% in 2030. Based on the greenhouse gas reduction strategies outlined in this Plan, Korea's energy intensity will decrease from 0.341 in 2007 to 0.185 in 2030.

2.4.5. Summary

Regarding the primary energy demand structure in the 2025 International Low Carbon Society Scenario of Ref. [17] (as shown in Fig. 3 below), coal is the most-used energy, while in Ref. [5] and Japan-2009 scenarios, oil is the most-used energy.

3. Methodology and approach

3.1. MARKAL model

The MARKAL (acronym for **MARK**et **AL**location) model is an energy system analysis tool based on linear programming. In response to the first global energy crisis, the International Energy Agency (IEA) established the Energy Technology Systems Analysis Program (ETSAP) in 1976 with the main purpose of building up member countries' energy system analysis capability, and it had succeeded in developing the MARKAL model. With the model's functions continue to expand over the years it has evolved to become a family of models. During the early years, the MARKAL model was widely used by most OECD countries for studying national or regional energy system planning in response to energy shortage issues. Currently, this model is mainly used by OECD countries and some developing countries for national, regional

and global greenhouse gas reduction strategy research related to the climate change issues. Because the MARKAL model has established its international credibility over the years, and as there are so many countries using this model, it is easy to make international comparison of results (e.g. CO_2 incremental costs for various countries). In Taiwan, the establishment of Taiwan's MARKAL model was completed in 1994 by ITRI's Green Energy and Environment Research Laboratories under the support of the Energy Bureau of the Ministry of Economic Affairs.

The main features of Taiwan's MARKAL energy engineering model (Fig. 4) are its abundant energy technology database, and the capability to continuously expand and incorporate new and advanced energy technology information. Based on the newest social and economic information and important parameters, this model is able to estimate the energy service demand for the industry, buildings and transportation sectors, and when incorporated with the conditions and assumptions of simulated scenarios, it can conduct various scenario simulations.

Eq. (2) shows the MARKAL model's objective function as follows:

$$\text{Min } C=\sum_t \frac{\text{ANNCOST}(t)\times\sum_{j=1}^{NY}(1+\text{DISCOUNT})^{(1-j)}+\text{INVEST}(t)-\text{SALVAGE}(t)}{(1+\text{DISCOUNT})^{NY\times(t-1)}} \tag{2}$$

where:

C: Discounted total system cost
ANNCOST(t): Annual system cost at time period t
INVEST(t): Investment cost at time period t
SALVAGE(t): Salvage value of technology at time period t

Based on the result of model simulations, the effects of energy and environment related strategies to the energy system can be evaluated. These effects may include for example, energy technology developing trend, primary energy and final energy changes, energy system total cost, and marginal cost reduction. Through the simulation result of various policies scenarios, we can also understand the impacts of various emission reduction strategies to energy system and the incurred costs. Thus, on the policy side, we are able to choose the scenario with the least cost, or combine various policies to mitigate the impact to the economic system.

This study uses the MARKAL model, with the energy service demand as the model's core driving force and the objective of cost minimization, to simulate the combinations of policies for specific energy market, product manufacturing, energy supply and technologies.

3.2. Scenarios and assumptions

3.2.1. Scenario design

The Taiwan government has announced its greenhouse gas reduction target and schedule that Taiwan's GHG emissions will return to the 2005 levels by 2020, and the 2000 levels by 2025. The purpose of this paper is to analyze the energy structure and CO_2 reduction costs in the BAU case (i.e., High GDP growth case), Low GDP growth case and four different CO_2 target cases as related to Taiwan's emission reduction targets. The key scenario assumptions and CO_2 emission pathways adopted in each scenario of this study are shown in Table 7 and Fig. 5 respectively.

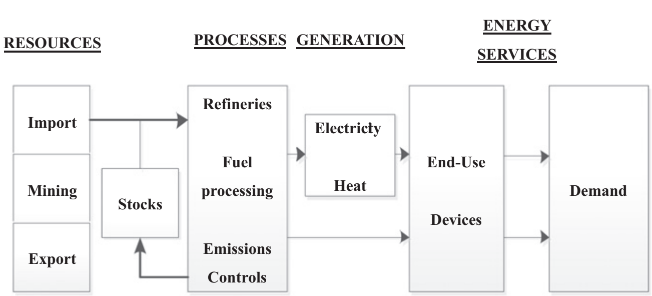

Fig. 4. Energy reference system of MARKAL model.

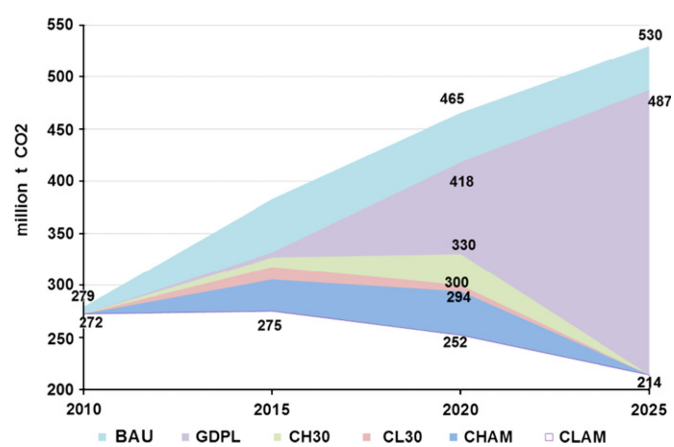

Fig. 5. CO_2 emissions in each scenario.

Table 7
Key scenario assumptions.

		BAU	GDPL	CH30	CHAM	CL30	CLAM
GDP	Average grow rate3.54%/yr from 2009 to 2025	⊙		⊙	⊙		
	Average grow rate 3.14%/yr from 2009 to 2025		⊙			⊙	⊙
CO_2 emission target	30% lower than in REF in 2020	–	–	⊙		⊙	
	Largest reduction amount in 2020				⊙		⊙
	Return to 2000 emission levels (214 Mt) in 2025			⊙	⊙	⊙	⊙
LNG	maintain at 2008 levels (822 Mt)	⊙	⊙				
	up to 1400 Mt in 2020			⊙	⊙	⊙	⊙
Renewable energy	Maintain at 2008 levels: total 2934.9 MW	⊙	⊙				
	Accumulated installed capacity 6388 MW in 2020			⊙	⊙	⊙	⊙
Energy saving	Energy tech. efficiency improve 0.4%/yr from 2009 to 2025	⊙	⊙				
	High efficiency technology			⊙	⊙	⊙	⊙
Nuclear energy	NPP1–NPP3 (note) normal decommissioning	⊙	⊙				
	NPP 1–NPP3 extend service			⊙	⊙	⊙	⊙
	NPP4 is deemed as the reduction measure	⊙	⊙				
	NPP4 operation			⊙	⊙	⊙	⊙
Coal-fired unit installedwith CCS (carbon removal efficiency 90%) device				⊙	⊙	⊙	⊙

Table 8
Taiwan's GDP growth rates as estimated by the TAIGEM model.
Source: TAIGEM [29].

Year	Gross domestic product grow rate (%/yr)	
	GDPL	BAU
2011–2015	3.58	5.30
2016–2020	3.29	3.61
2021–2025	3.04	2.63

Table 9
Taiwan's population and household grow rate forecast values.
Source: Council for Economic Planning and Development [2], TAIGEM [29].

Year	Population (%/yr)	Household (%/yr)
2006–2010	0.31	1.71
2011–2015	0.31	1.63
2016–2020	0.21	1.41
2021–2025	0.09	1.23

Table 10
Taiwan's industrial structure forecast values (unit:%).
Source: TAIGEM [29].

Year	Agriculture	Industry	Service
2010	1.49	30.95	67.56
2015	1.16	30.87	67.96
2020	1.46	30.51	68.03
2025	1.36	29.47	69.17

Table 11
Taiwan's import energy price forecast values (dollars per unit, 2007 prices).
Source: ITRI (2009).

Year	Crude oil (barrel)	Coal (tonne)	Coke (tonne)	LNG (tonne)
2010	68.82	54.84	118.60	444.93
2015	102.93	56.52	119.73	470.08
2020	105.51	55.18	119.97	507.05
2025	109.97	56.19	124.33	549.15

3.2.2. Assumptions adopted in the MARKAL model

When the MARKAL model is used to conduct energy service demand estimation, the information it needs include GDP, industry structure, population, and the number of households. In this aspect, the following assumptions are adopted:

- Population growth rate:0.23%/yr;
- Number of households growth rate: 1.5%/yr;
- Prices of energy in 2025: Crude oil US$109.97/barrel; fuel coal US$56/tonne; raw material coal US$124/tonne; liquefied natural gas US$549/tonne.

Details of the social and economic assumptions and their descriptions are listed in Tables 8–11. The GDP growth rates after 2010 are calculated based on the economic growth rates estimated by the TAIGEM model from the National Tsing Hua University Sustainable Development Research Center (2010), and presented in Table 8 below.

4. Results

4.1. Simulation results

4.1.1. Energy structure

As shown in Fig. 6, the annual energy supply growth rates of the BAU (i.e., GDP-High Growth, "GDPH") scenario and the GDP-low growth ("GDPL") scenario are 1.8%–2.4% from 2008 to 2025, and the annual energy supply growth rate of the other four emission reduction scenarios (CH30, CL30, CHAM, and CLAM) decrease to 1.3%–1.5%respectively. The energy supply in the BAU scenario is greater than in the GDPL scenario due to the higher share of upper and middle stream chemical raw material industries in the industry sector, and the higher share of oil supply than coal. The various emission reduction scenarios' total energy supply in 2020 and 2025 are reduced by about 12% relative to the BAU scenario. The share of coal and oil is more than 87% in the BAU Scenario, thus this share can be reduced to 73%–76% in the various emission reduction scenarios.

4.1.2. Power generation

The BAU (GDPH) scenario's electricity demand growth rate is 3.7%–5.6%in 2025 (see Fig. 7) and additional coal power generation

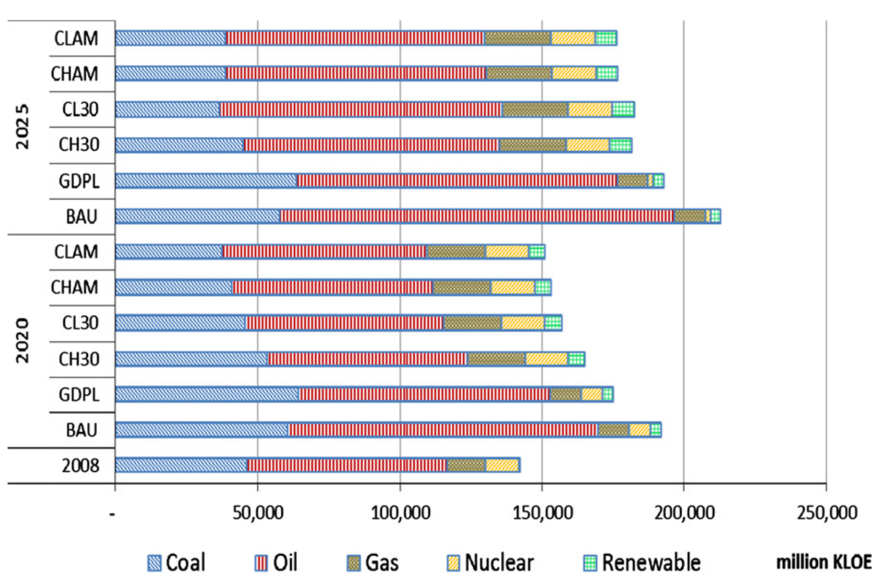

Fig. 6. The energy supply structure for various scenarios.

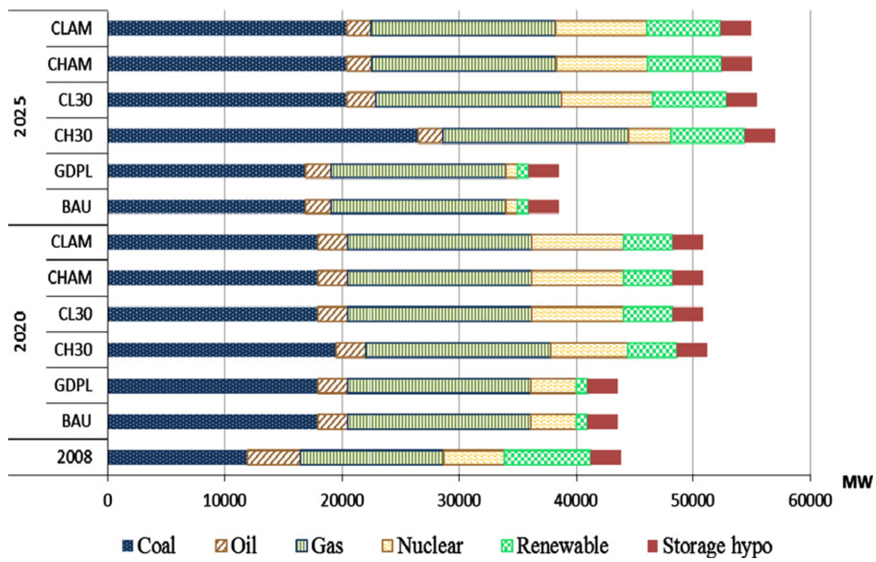

Fig. 7. The power generation structure for various scenarios.

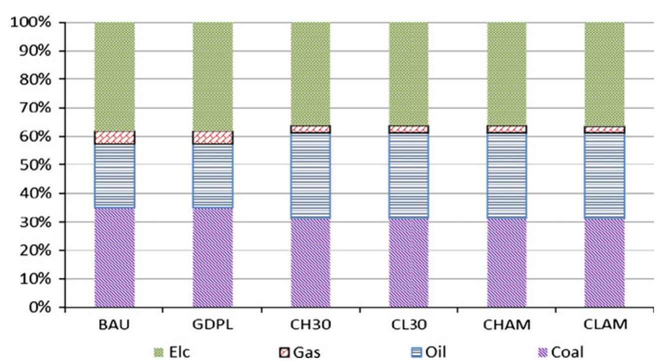

Fig. 8. The energy demand structure of industry sector in 2025 (by scenario).

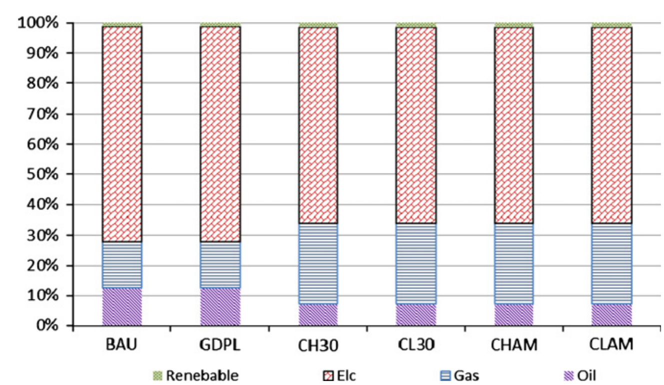

Fig. 9. The energy demand structure of buildings sector in 2025 (by scenario).

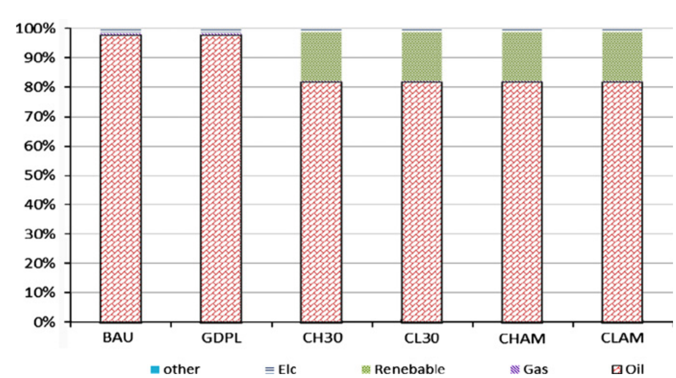

Fig. 10. The energy demand structure of transportation sector in 2025 (by scenario).

in BAU and GDPL scenarios are required in order to make up for the power generation shortage due to nuclear power decommissioning. The annual electricity demand growth rate of the four emission reduction scenarios decrease to 2%–2.6% (Fig. 7).

No new pumped storage hydropower capacity is added in any scenario. Nuclear power, gas power generation and renewable energy power generation all share the installed capacity target designated by the energy policies. In order to comply with the CO_2 emission limitations, various emissions reduction programs increase electricity consumption efficiency through adopting energy saving technologies, while nuclear, gas or coal power generation are used as the base load units.

4.1.3. Energy demand by sector

The same as in the electricity sector, the energy demand of the industry sector in the BAU scenario is higher than in the GDPL scenario (Fig. 8). In the four emissions reduction scenarios, the energy demand of the CH30 scenario (without nuclear power) is the smallest (Fig. 8), while the energy demand for the other three scenarios are slightly different depending on high and low CO_2 emission limitations. Regarding the shares of different energies used in each scenario, the shares of oil range from 22.3% (BAU Scenario) to 30% (emission reduction scenarios), as the former has lower incremental cost, and there are less emission reduction technologies to be selected for some petrochemical industries.

As shown in Fig. 9, the shares of energies for the buildings sector in the BAU scenario are similar to the GDPL scenario. For the four emission reduction scenarios, the energy demand for CH30 is the smallest, while the energy demand in the other three scenarios are slightly different depending on the high and low CO_2 emission limitations. Regarding shares of different energies in each scenario, natural gas will replace electricity and oil due to government's natural gas target.

The same as in the buildings sector, the energy shares of the BAU Scenario and the GDPL Scenario are similar for the transportation sector (Fig. 10). Regarding different energy shares in each scenario, conventional fossil oil is being replaced following

government's biomass energy targets in order to reduce the greenhouse gas emissions (Fig. 10).

4.1.4. Incremental costs by sector

The MARKAL model is used to find out the solution to the smallest cost of energy demand and supply combinations for the entire period, under the conditions of compliance with CO_2 emission limitations. The incremental cost of each reduction measure depends on the energy efficiency technology chosen for that period or the kind and cost of alternative transportation fuel. The reduction potential of each measure (e.g., the CO_2 reduction described in the previous section), can be used to calculate the cost according to the quantity of high efficiency facility used by this reduction measure. In addition, the increased cost of emission reduction can also be calculated using investment cost, maintenance cost and fuel cost.

The total incremental cost of each emission reduction scenario relative to the BAU scenario is shown in Fig. 11. Because the MARKAL model uses the energy system combination to find a solution with the lowest cost for the whole period, in order to reach the emission reduction targets of 2020 and 2025, the two emissions reduction programs (CH30 and CL30) will start to phase out old equipment and increase new equipment with high efficiency beginning 2015, so that the total incremental cost is the highest in 2015 as it increases 27% relative to BAU (2.8%–3% of GDP). During 2020 and 2025, since some high efficiency equipment has already been invested in the previous period, their incremental costs decrease slightly by only 20%–21%and 2%–7% relative to BAU respectively (2.3%–2.4% and 0.2%–0.8% of GDP respectively). Similarly, the emissions reduction programs (CHAM and CLAM) also start to phase out old equipment and install high efficiency new equipment beginning 2015, but because the extent of reduction in 2025 is so large, it is necessary to install more high efficiency equipment to meet the emission reduction requirement, thus the incremental cost of 2025 (16%–18% relative to BAU, 1.6%–1.8% of GDP) is higher than both the 2015 cost (12%–14% relative to BAU, 1.2%–1.4% of GDP) and 2020 cost (6% relative to BAU, 0.6% of GDP). As all four emission reduction scenarios must return to 2000 CO_2 emission levels by 2025, depending on its high or low GDP growth and the extent of emissions reduction under the BAU scenario, the total incremental costs for the four emission reduction scenarios will be in the order (from high to low cost) of CH30, CL30, CHAM, and CLAM. The accumulated incremental cost increase will be 14%, 13%, 10%, and 9% respectively relative to BAU (1.83%, 1.68%, 1.29%, and 1.16% of GDP).

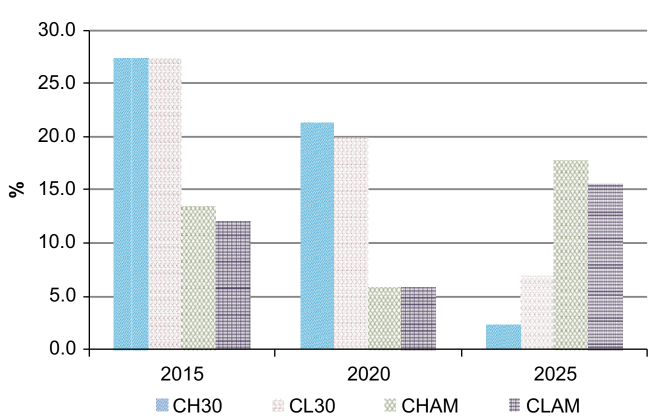

Fig. 11. Total incremental cost increase rate for reduction scenario relative to BAU scenario.

4.1.5. CO_2 index

The CO_2 index for each scenario is listed in Figs. 12–14. As can be seen, the per capita emissions in 2020 are between 11.1–14.4 tonnes and 9.5 tonnes in 2025. The emission intensities in 2020 are between 13.8 and 16.1 g/US$, and between 9.2–9.9 g/US$ in 2025. The energy intensities in 2020 are between 7–8.4 liter-oil equivalent/US$, and 6.5 liter-oil equivalent/US$ in 2025.

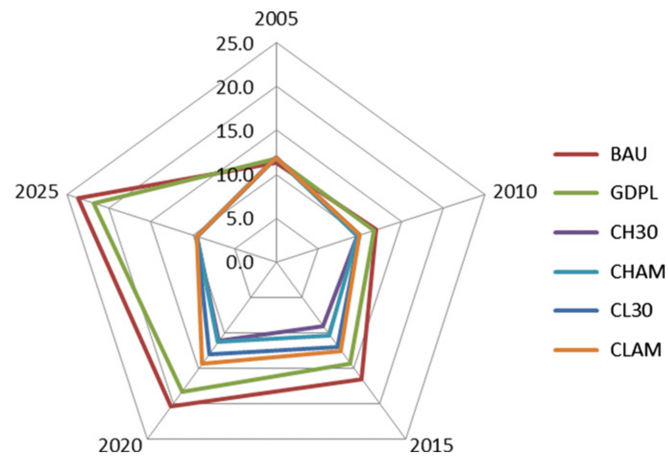

Fig. 12. Per capita emission of CO_2 (tonne/person) in each scenario.

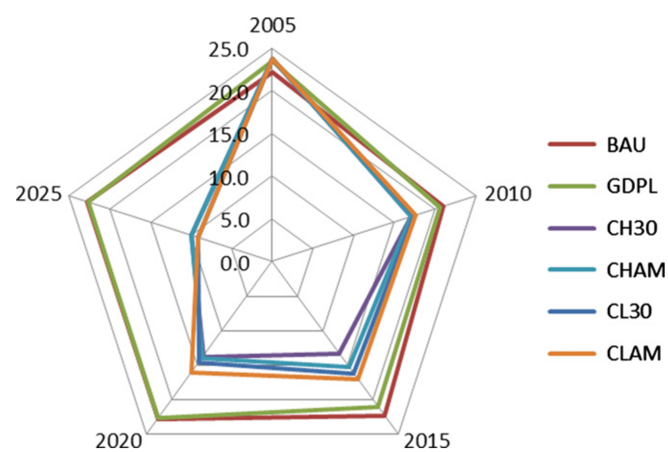

Fig. 13. Emission intensity (g/US$) in each scenario.

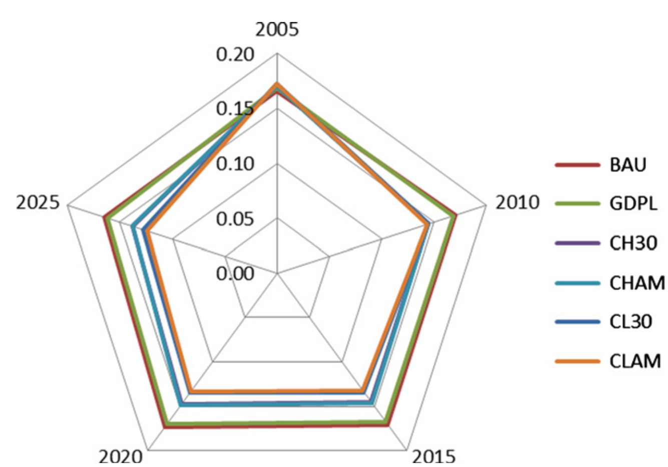

Fig. 14. Energy intensity (toe per US$) in each scenario.

5. Discussions

Under Ref. [17] scenarios, the annual energy demand growth rate is from 2.26%/yr in 2010 decrease to 1.5%/yr in 2025, energy intensity decreases from 0.2 to 0.13–0.15 in the same period. Under Japan-2009 scenarios, the annual energy demand growth rate is from −0.28%/yr in 2010 increases to −0.1%/yr in 2025, energy intensity decreases from 0.13 to 0.07 in the same period. Korea energy intensity target is 0.19 in 2025. Under Taiwan's scenarios, the annual energy demand growth rate of both BAU scenario and GDPL scenario is more than 1.8%/yr, and it decreases to 1.4%/yr in the four emission reduction scenarios, which is close to the growth rate reported in Ref. [17]. Taiwan's energy intensity is also similar in Ref. [17] scenarios, but higher than in Ref. [5] scenarios.

For the four emission reduction scenarios, in 2025 a decrease of 56%–60% relative to the BAU Scenario, and a decrease of 15% relative to 2005 levels is reported. This result is higher than the Carbon Reduction targets in Table 5, and also higher than reported in Refs. [17,5] scenarios. The total incremental cost is the highest in 2015 as it increases 12%–27% relative to BAU. The increases are 2%–21% relative to BAU in 2020, and 2%–18% relative to BAU in 2025. The increase in accumulated incremental cost will be 9%–14% relative to BAU.

To attain the CO_2 target, Taiwan needs to adopt higher efficiency technologies. This is because Taiwan's economy continues to grow, but 98% of Taiwan's energy demand relies on imports from oversea sources, plus limited natural endowments of domestic renewable energy, as well as the limitation of imported natural gas. Thus, nuclear power and oil combined account for a high share in Taiwan's energy demand structure, while renewable energy only accounts for a small share in Taiwan's power generation structure.

For Taiwan, it is very difficult to reach the GHG reduction target just by relying on emission mitigation technology, thus, how much GHG reduction responsibility Taiwan should bear is a critical issue. Besides, in addition to reducing greenhouse gas emission through economic incentive mechanism and consumer behavior change, it is also necessary for Taiwan to be able to participate in the flexible mechanisms of UNFCCC.

6. Conclusion

Since the United Kingdom first initiated the "Low Carbon Society" concept, several Annex I countries (Japan, Europe etc.) and non-Annex I countries (e.g., Korea) have also followed suit in promoting their transition to the low carbon society by encouraging their domestic green energy, greening of industry, and developing new technologies. After the COP 15 Copenhagen Conference, more than 70 countries (both Annex I countries and non-Annex I countries) have submitted their 2020 reduction commitments. In 2008, during Taiwan's Third National Energy Conference, a national consensus was reached that in the future the government will take steps to establish a low carbon society with low carbon communities, low carbon cities and low carbon regional circles which comply with Taiwan's sustainable development target. In order to map out the CO_2 emission mitigation strategies matching these goals, this study referred to international organizations, such as IEA and major countries' studies which set the emission reduction scenarios for different technology development speeds under the same reduction target, in setting four different emission reduction scenarios. This study also coordinated with Taiwan NAMAs Negotiation Meeting's decision on social and economic scenario assumptions to estimate the energy service demand of the industry, buildings and

Table A1
The assumptions and conditions of international low carbon scenario.

	WEO [17]	United Kingdom	USA(AEO2011)	Japan-2009	Korea
Evaluation Model	World Energy Model (WEM)	MARKAL-ED Model	NEMs Module	Long-term Energy Outlook(2009) Engineering-economic model	
BAU Definition	Current Policies Scenario: Continue current policies		Contain current policies and measures, known technologies and its future development	At its current economic, social and policy situation to continue the development.	
Reduction scenario definition	1. New Policies Scenario: various countries respond reduction commitment to Copenhagen Accord. 2. 450 ppm: reduce 25–30%/17–25% relative to 1990/2005.	Various scenario reduction goals in 2050 are 40%–90% reductions relative to baseline scenario.	1 No Sunset case: renewable energy power generation tax remission, industries and architecture high efficiency equipment tax remission 2 Extended Policies case: in addition to renewable energy power generation tax remission, industries and architecture high efficiency equipment tax remission, update the Federal equipment efficiency standard (includes ENERGY STAR, ECC, CAFÉ)	1. Technology developing scenario: energy saving technology and new technology enter the market quickly. 2. Sensitivity analysis scenario: conduct high economic growth and high energy prices sensitivity analysis.	
GDP	2008–2035 is 3.2%/yr (IMF)		2010–2020 average growth rate is 1.5%/yr, 2020–2030 average growth rate is 1.1%/yr.		2000∼2050 is 2%/yr
Population	2008–2035 is 0.9%/yr		2010–2030 average growth rate is 1.3%/yr		
Energy price	2035 crude oil US$90–135/barrel, Natural gas US$9.7–16.5/MBtu, fuel coal US$62.1–115/tonne		2030 crude oil US$45/barrel; natural gas US$364/barrel; fuel coal in 2030 US$51/tonne.		
CO_2 price	2035 US$42–120/tonne				
Technical progress	New policy scenario has no new measure to promote reduction, technical progress speed is slowest. 450 ppm reduction scenario has the fastest technical progress speed.			Industry carry out Keidanren's Voluntary Action Plan, residential, service business and transportation carry out Top-runner Approach	

transportation sectors. This study then adopted low carbon society structure development as the target, and applied the MARKAL energy engineering model, to conduct the emission reduction strategies research and evaluation of Taiwan's electricity, industry, buildings, and transportation sectors, and analyzed the scenarios for short-term and mid-term adoption of clean energy, as well as the reduction potential of high efficiency energy saving technology and associated incremental costs.

The MARKAL model is then used to find the solution of energy system combinations with the smallest cost for the whole period. The simulation results show that in order to reach the emission reduction targets of 2020 and 2025, all reduction scenarios will have to start phasing out old equipment and add new high efficiency equipment beginning 2015. Thus, the accumulated incremental cost increase will be 9%–14% relative to BAU.

The annual energy demand reduction rate in Taiwan's emission reduction scenarios is around 1.4%, close to the value presented in Ref. [17]. But in Taiwan's reduction scenarios, the energy demand reduced by 56%–60% relative to baseline scenario in 2025, and by 15% relative to 2005 levels, higher than in both WEO scenario and AEO scenarios, while Taiwan's energy intensity is similar in Ref. [17], but lower than in Japan-2009 scenarios. This is due to Taiwan's economy continues to grow, but its energy system which relies highly on imported energy from overseas sources, plus there is a limitation for Taiwan to use low (or non-) carbon energy in reducing emissions. For Taiwan, it is very difficult to reach the emission reduction target just by relying on emission mitigation technology. Thus, besides the crucial issue of how much GHG reduction responsibility Taiwan should bear, as well as how to reduce GHG emissions by promoting economic incentive mechanism and consumer behavior change, it is also necessary to allow Taiwan to participate in the international flexible mechanisms. Such participation will also benefit the international community's GHG reduction efforts tremendously.

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Annex I

See Annex I Table A1.

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